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COMPARISON OF LOWER-FREQUENCY (<1000 Hz) DOWNHOLE SEISMIC SOURCES FOR USE AT ENVIRONMENTAL SITES*

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ABSTRACT

In conjunction with crosswell seismic surveying being done at the Hanford Site in south-central Washington, four different downhole seismic sources have been tested between the same set of boreholes. The four sources evaluated were the Bolt airgun, the OYO-Conoco orbital vibrator, and two Sandia-developed vertical vibrators, one pneumatically-driven, and the other based on a magnetostrictive actuator. The sources generate seismic energy in the lower frequency range of less than 1000 Hz and have different frequency characteristics, radiation patterns, energy levels, and operational considerations. Collection of identical data sets with all four sources allows the direct comparison of these characteristics and an evaluation of the suitability of each source for a given site and target.

INTRODUCTION

Crosswell seismic imaging is emerging as a viable tool for aiding in the characterization and monitoring of environmental sites. These sites, which are often unsaturated and composed of unconsolidated material, provide a challenge for creating seismic sources small enough to be fielded in standard-sized boreholes, yet still provide enough energy to propagate needed distances and have a high enough frequency content to provide the necessary resolution. Several sources have been developed to meet these needs and comparison of these source is critical to determining the appropriate choice for the restrictions at any given site. In this paper we concentrate on lower-frequency sources, mostly mechanical in nature, that will not yield the resolution of the higher-frequency sources, but should be able to propagate seismic waves farther distances.

Experiment Configuration

The test location used for the source evaluation is an environmental remediation site located in the 200 West area of the Hanford Site in south-central Washington. Data were taken in the vadose zone using existing steel-cased, ungrouted boreholes. The entire survey was in gravel and sand dominated sequences of the flood-deposited Hanford Formation. The source and receiver wells were separated by 70 m. For testing purposes, the particular source being used was held fixed at 15 m depth and the receiver was moved in 1 m intervals from the surface to 20 m depth.

The OYO Geospace downhole three-component accelerometer package, a rigidly clamped receiver, was used to detect the signals generated. Data were recorded on an EG&G ES2420 seismic recording system at a sample rate of 0.5 ms with an anti-alias filter of 720 Hz.

SOURCES

The four sources tested were the Bolt airgun, the OYO Geospace-Conoco orbital vibrator, the Sandia pneumatic vertical vibrator, and the Sandia magnetostrictive vertical vibrator. Of these sources, only the airgun and the orbital vibrator are currently commercially available. Each of these sources varies in frequency and energy

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output characteristics, as well as in requirements for operation and the ease of operation itself.

Airgun

The airgun used for this experiment was the Bolt Model DHS-5500. The airgun consists of a pressurized chamber and a quick-release solenoid valve. When triggered, the solenoid valve rapidly releases the gas into the borehole resulting in a pressure pulse that converts to both compressional (P) and shear (S) seismic energy radiating out from the hole. The tool is 5 cm (2 in) in diameter an approximately 61 cm (2 ft) long, depending on the size of the pressure chamber used. There are three pressure chambers available, 82, 164, and 410 cm^3 (5, 10, or 25 in^3). Gas pressures up to 2000 psi can be used.

The airgun couples through the borehole fluid and, thus, requires a fluid-filled borehole. Because this experiment was conducted above the water table, a packer was placed in the source well below the deepest source depth, and the hole above the packer filled with water to provide the coupling medium needed. Coupling through the borehole fluid and the lack of need for rigid clamping allows the airgun to be rapidly deployed and moved. In addition, the impulsive nature of the source requires only short recording times and very little post-processing of the data.

For this test, a gas pressure of only 500 psi, supplied by bottled nitrogen, was used to avoid any damage to the boreholes, and the largest pressure chamber was installed. The tool was fielded using a standard seven-conductor wireline with an additional high-pressure gas line that was strapped to the wireline as the tool went downhole. Data were recorded for 1.0 s after the trigger pulse, and an accelerometer on the source provided a sharp time break for zero time.

Orbital Vibrator

The orbital vibrator was developed by Conoco, Inc. and is being marketed by OYO Geospace. It consists of an eccentric mass that is spun by a DC motor around a horizontal axis. By varying the voltage to the motor, a sweep of frequencies with both P and S wave components is generated. This source sweep is recorded by an accelerometer mounted in the source. The tool is 10 cm (4 in) in diameter, 76 cm (2.5 ft) long and runs on a standard seven-conductor wireline. Coupling with the formation is again through the borehole fluid, increasing the speed at which the tool can be moved, but requiring the source borehole at this site to be packed off and filled with water as with the airgun. A clamping mechanism for the orbital vibrator is presently under development and will allow it to be used in dry boreholes. Although the unit used for this test was a single motor and mass design, a dual motor and mass design is becoming available and should approximately double the power output of the source.

In this experiment, increasing voltage was applied for 3 s and then removed, allowing the source to spin down for approximately 5 s giving a total sweep length of 8 s. Data were recorded for 8.1 s. The voltage was then reversed causing the mass to rotate in the opposite direction, and a second sweep was recorded in the same manner. Combining the data from the forward and reverse spin directions will allow decomposition of the data into the P and S components, but this has not been done for the data shown in this paper. The frequencies generated range from 90 to 440 Hz (Figure 1).

Processing for all the vibratory sources in this test, including the orbital vibrator, is the same. The data are whitened and a minimum phase filter is derived from the source trace recorded by the sensor on the tool. This filter is applied to all the recorded traces. The data are then crosscorrelated with the source trace and bandpass filtered to include only the frequencies generated by the source as determined by the spectra from the source traces in Figure 1.

Pneumatic Vibrator

The pneumatic vibrator is a prototype source developed at Sandia National Laboratories (Hardee et al., 1987). It consists of a rotary valve connected to a DC motor that controls the porting of compressed gas to a vertical piston chamber. The oscillation of the piston in this chamber generates primarily vertically-polarized S waves and some P-wave energy. The voltage to the rotary valve motor is computer controlled, and a frequency sweep is designed on the computer, relayed to the source, and monitored both by a tachometer on the rotary valve

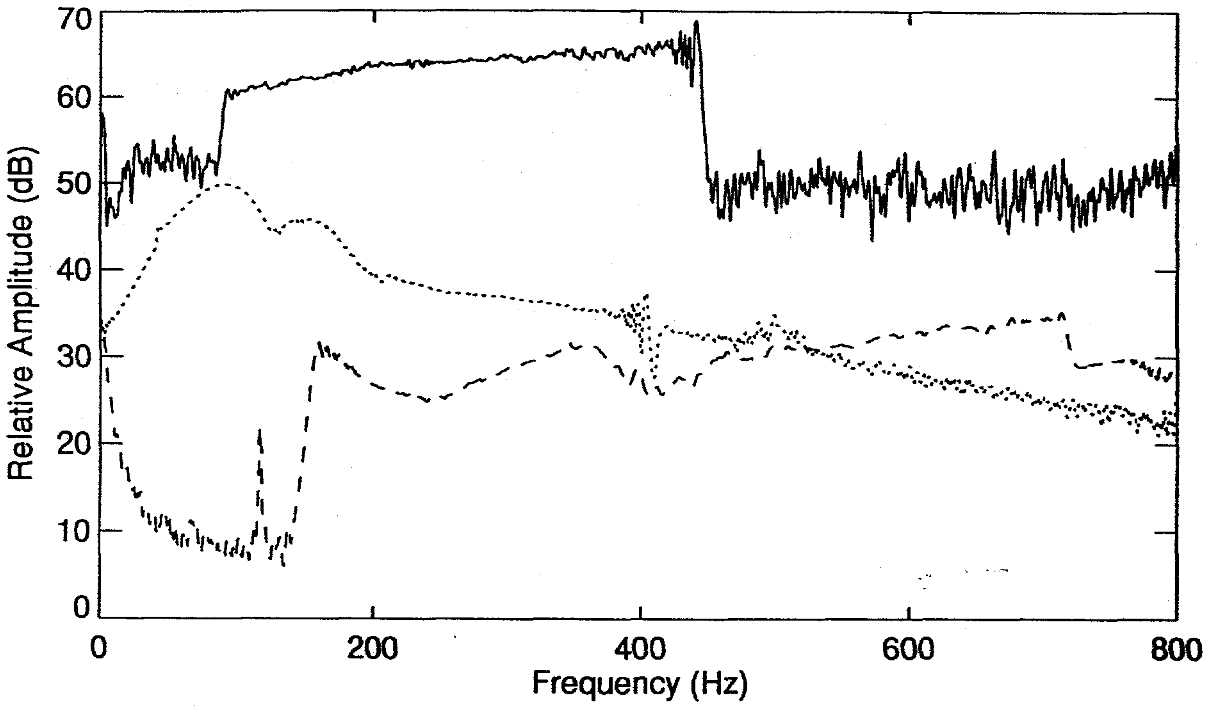

Figure 1: Comparison of source spectra for orbital (solid), pneumatic (dotted), and magnetostrictive (dashed) vibrators. Amplitudes do not correlate between sources due to variations in sensors and recording parameters. Airgun had no sensor to record a source signature.

motor and by a geophone mounted in the tool. The tool is 5 cm (2 in) in diameter and 4.3 m (14 ft) long, most of which is reservoir space for the compressed gas. It is deployed on a standard seven-conductor wireline with an additional high pressure hose that, like the airgun, is strapped to the wireline as the tool goes downhole. A normal operating pressure of 120 psi is supplied from nitrogen bottles at the surface.

Sweeps were run from 40 to 400 Hz (Figure 1) in 7.6 s with data recorded for 8.0 s. A total of four sweeps were run at each source location and the data are stacked together after completing the same processing stream described for the orbital vibrator. The pneumatic vibrator, unlike the airgun and orbital vibrator, is rigidly clamped into the borehole with a clamp located just below the piston chamber. This allows it to function in dry and fluid-filled boreholes, although the time needed to clamp and unclamp significantly slows down the rate at which data can be taken.

Magnetostrictive Vibrator

The magnetostrictive vibrator is another prototype tool being developed at Sandia. This is again a vertical vibrator based on a spring pre-loaded magnetostrictive actuator rod with permanent magnet bias and drive coils and an integral 13.6 kg (30 lb) tungsten reaction mass. It is driven using a programmed amplitude and frequency varying sinusoidal sweep signal through a large audio amplifier. The amplitude variation is used to flatten the spectrum through the frequency sweep and the degree of variation is determined by the signal from an accelerometer mounted in the source. The tool is again deployed on a standard seven-conductor wireline and is 10 cm (4 in) in diameter and 76 cm (2.5 ft) long. It clamps rigidly into the borehole at a much more rapid rate than the pneumatic vibrator, so still deploys fairly rapidly and can be used in fluid-filled or dry boreholes.

Although the source is capable of generating frequencies from 150 to 2000 Hz, the upper end of the sweep was restricted to 720 Hz due to sampling rate and anti-alias filter restrictions. This frequency range was swept in 7.8 s and data recorded for 8.0 s. The same processing stream described for the other vibrators was employed to process the data from the magnetostrictive vibrator, using the data recorded from the accelerometer mounted on the tool for the crosscorrelation process.

COMPARISON OF DATA

The data generated by each of these sources and recorded in the receiver borehole is analyzed in terms of the final signal-to-noise ratio, the relative strength of the P and S waves received, and the overall complexity of the data.

Signal-to-Noise Ratios

Signal-to-noise ratios for the vertical component accelerometer in the receiver package were calculated by taking portions of the signal recorded with both the source and receiver at 15 m depth and transforming them into the frequency domain. Three windows were used: a noise window from .01 s to .09 s, a P-wave arrival signal-plus-noise window from .10 s to .15 s and S-wave arrival signal-plus-noise window from .15 s to .20 s. These windows were shifted forward in time by .01 s for the airgun data due to a discrepancy in the arrival times between the impulse-type data of the airgun and the crosscorrelated data of the vibratory sources. The noise spectra are then plotted along with the P and S wave signal spectra for each of the sources in Figures 2 to 5.

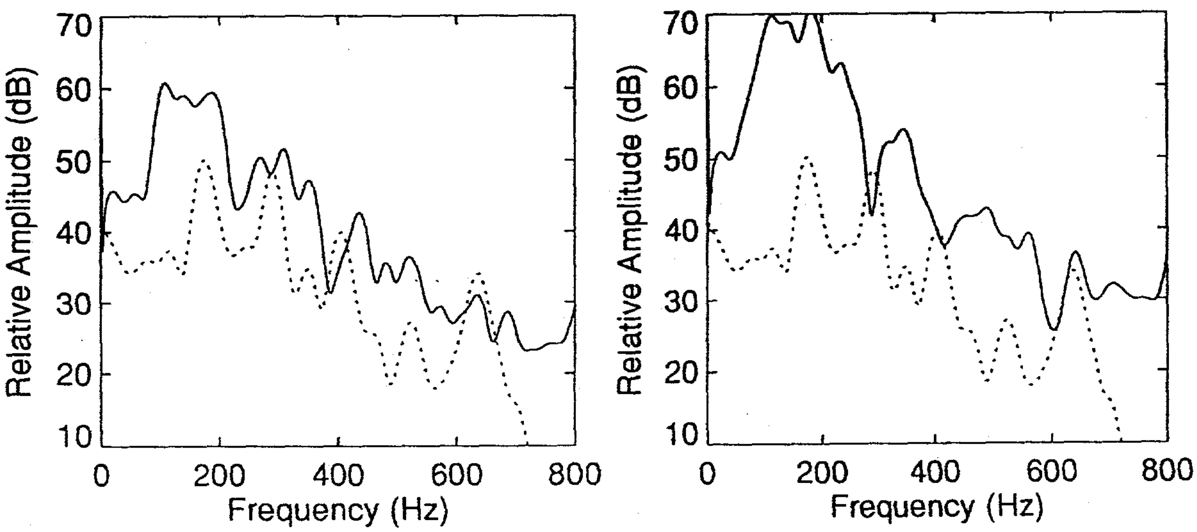

Figure 2: Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for the airgun.

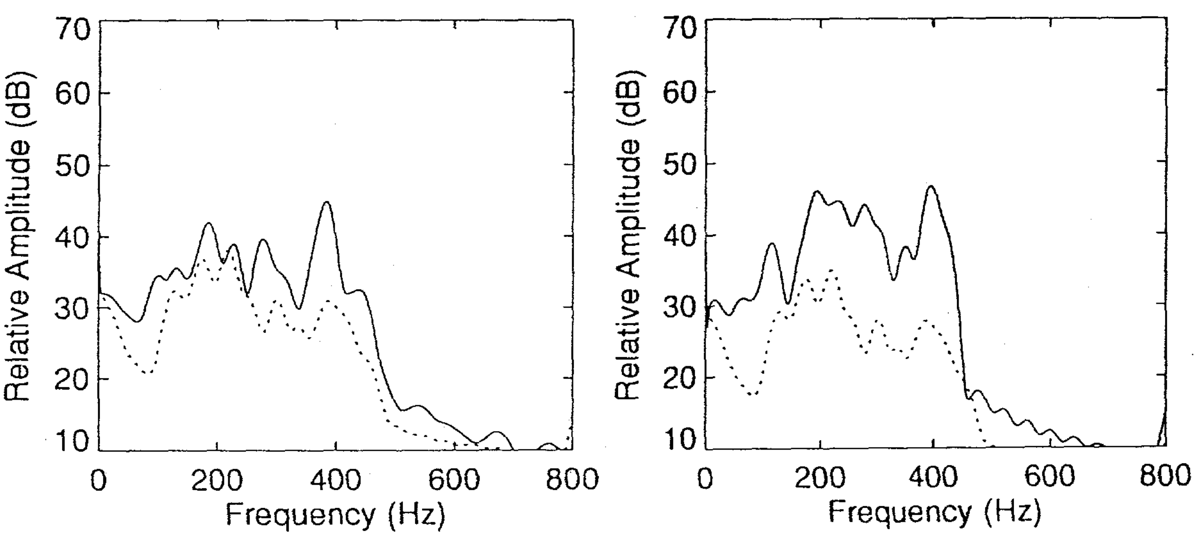

Figure 3: Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrival for orbital vibrator.

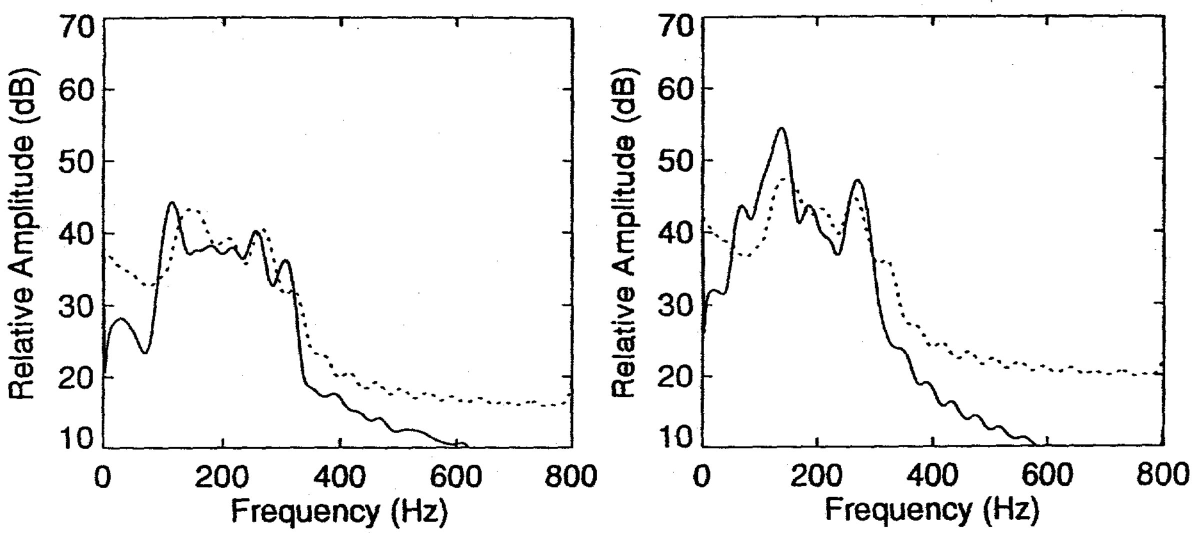

Figure 4: **Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for pneumatic vibrator.**

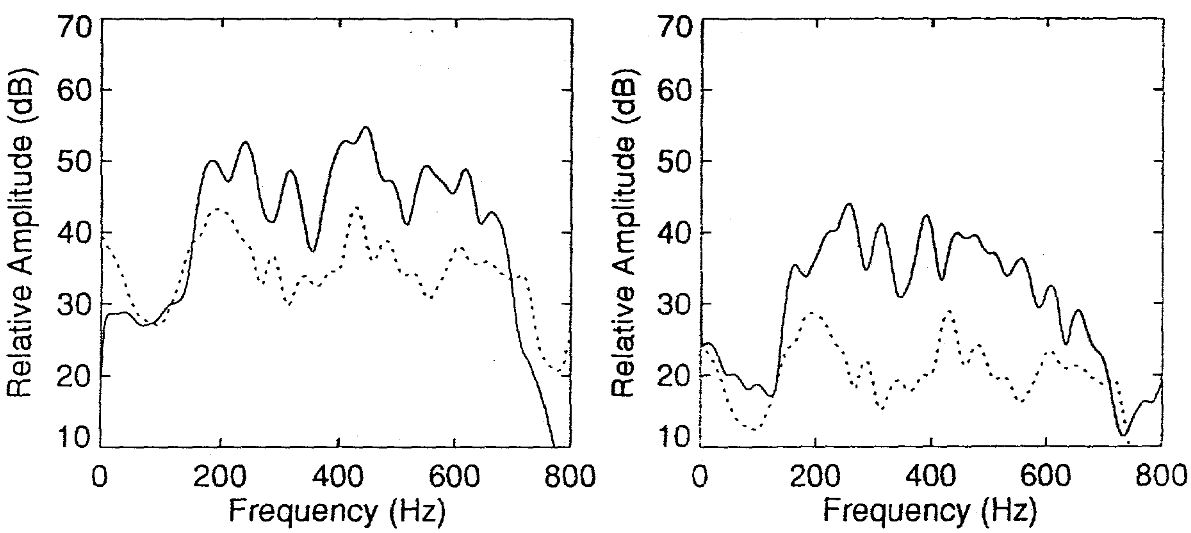

Figure 5: Signal (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for magnetostrictive vibrator.

The amplitude scales on these figures are relative amplitude and are not the same scale from source to source.

For the airgun source (Figure 2), there is in general good signal-to-noise characteristics out to 600 Hz for both the P and S arrival, though the signal-to-noise for the P wave is about half that of the S wave. The majority of the noise is from the $\approx$ 60 Hz electrical noise and its harmonics. Notch filtering can remove some of this noise, but tends to smear the first arrival energy making first arrival picks more ambiguous.

The orbital source (Figure 3) shows good signal-to-noise characteristics for the S wave across the frequency band generated by the source, but tends to have a much weaker P-wave arrival, especially at the lower end of the frequencies generated. Completing the processing of the data by combining the forward and reverse spin directions should improve this, but the P-wave arrival will probably still be weak.

The pneumatic source has the worst signal-to-noise characteristics of the sources tested. This source should generate primarily vertically-polarized S-wave energy in the horizontal direction, so it is not surprising that there is no obvious P-wave energy. The S-wave energy, however, still shows poor signal-to-noise ratios, although there is some energy in the 50 to 150 Hz range.

Finally, the magnetostrictive vibrator shows the most favorable signal-to-noise characteristics. As for the pneumatic vibrator, the radiation pattern is such that P-wave energy should be fairly small in horizontal travel paths, but there is still reasonable signal-to-noise for the P-wave arrival over the full source frequency range from 150 to 720 Hz. The S-wave arrival has an even greater signal-to-noise ratio over the same frequency range, although it drops off slightly above 600 Hz.

Individual Traces and Source Gathers

Based on the signal-to-noise ratios, the pneumatic vibrator data were additionally filtered with a bandpass from 30 to 220 Hz. A direct comparison of the vertical component traces recorded with the source and receiver both at 15 m depth for all four sources is shown in Figure 6. These are trace normalized records so direct amplitude comparisons are not possible, but the general signal-to-noise characteristics and the frequency content of the traces from the different sources can be compared.

P and S-wave arrival times are marked on Figure 6 based on the airgun data. The P-wave arrival is most clearly seen on the airgun data and again on the magnetostrictive data. There is some change in character at the P-wave arrival time on the orbital data, but this is not a clear arrival. S-wave arrivals are seen on all four data sets, again most clearly on the magnetostrictive and airgun data.

Arrival times on impulsive sources are picked at the initiation of the energy. On vibratory sources, however, the crosscorrelation process creates a wavelet with the arrival time at the center of the wavelet, not the beginning. With this in mind, a discrepancy in arrival times of about .005 s between the airgun and the vibratory source is seen in Figure 6. This is a result of the processing of the vibratory data and has been noted in previous studies (Howlett, 1991).

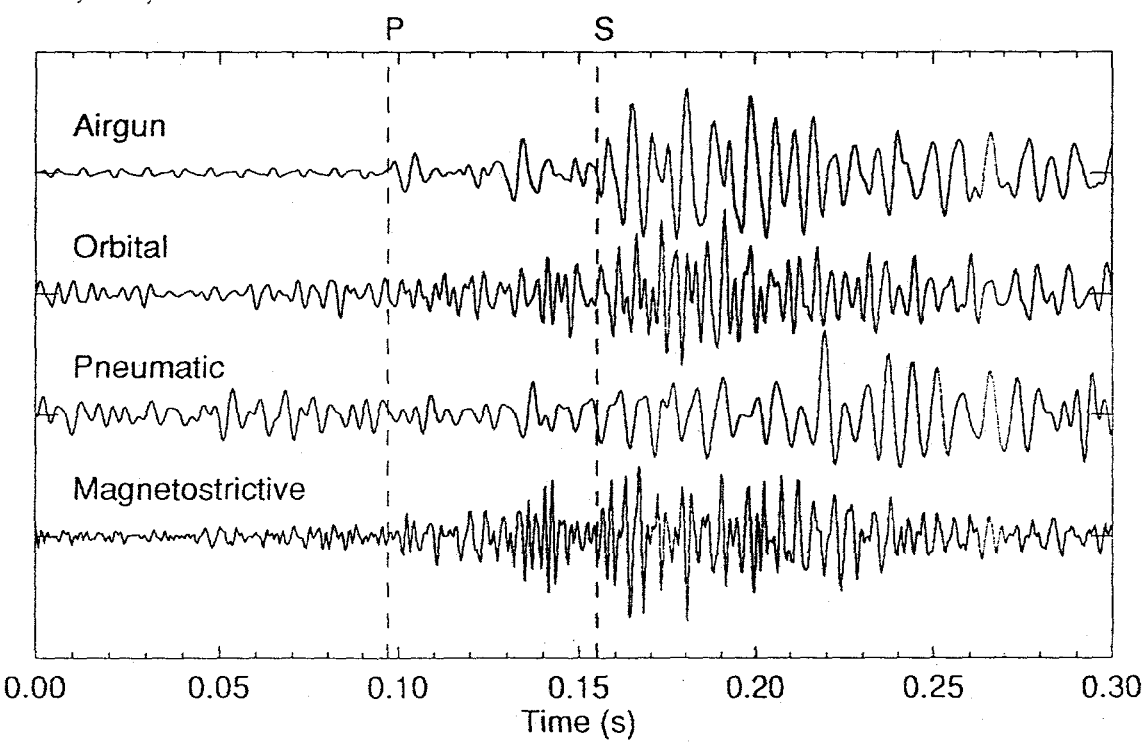

Figure 6: Comparison of trace recorded with both source and receiver at 15 m depth for all four sources.

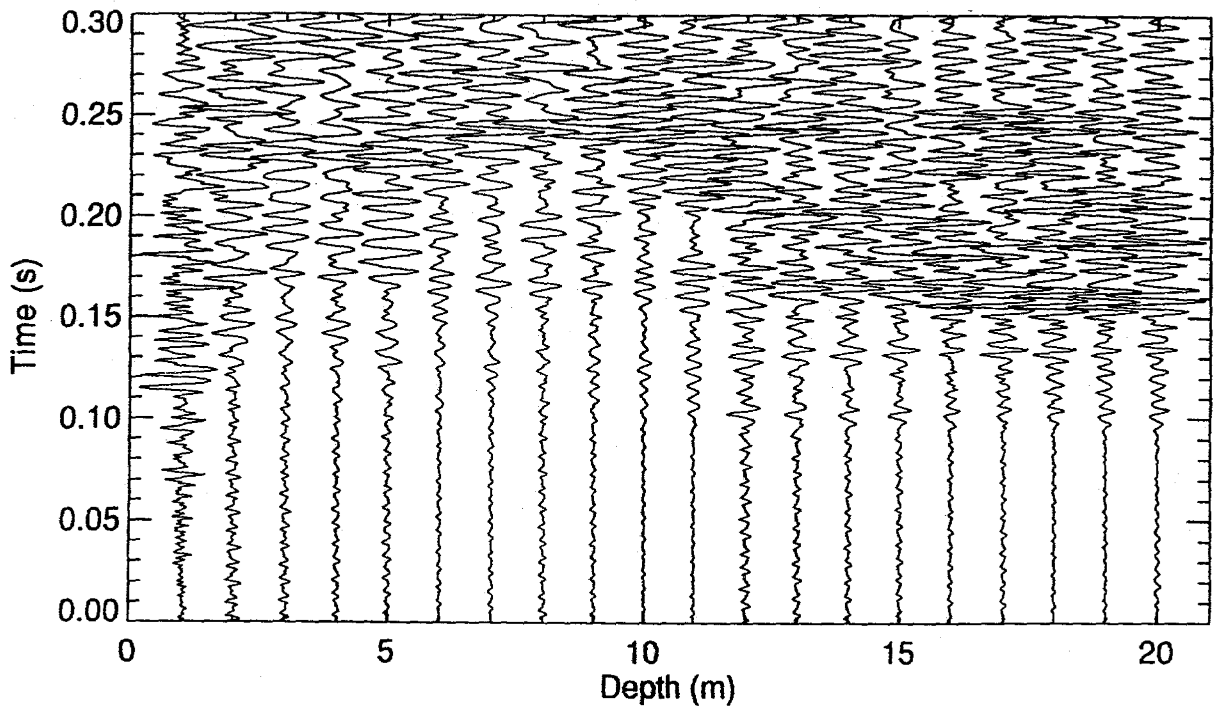

Figure 7: Source gather for data collected with airgun with source at 15 m depth.

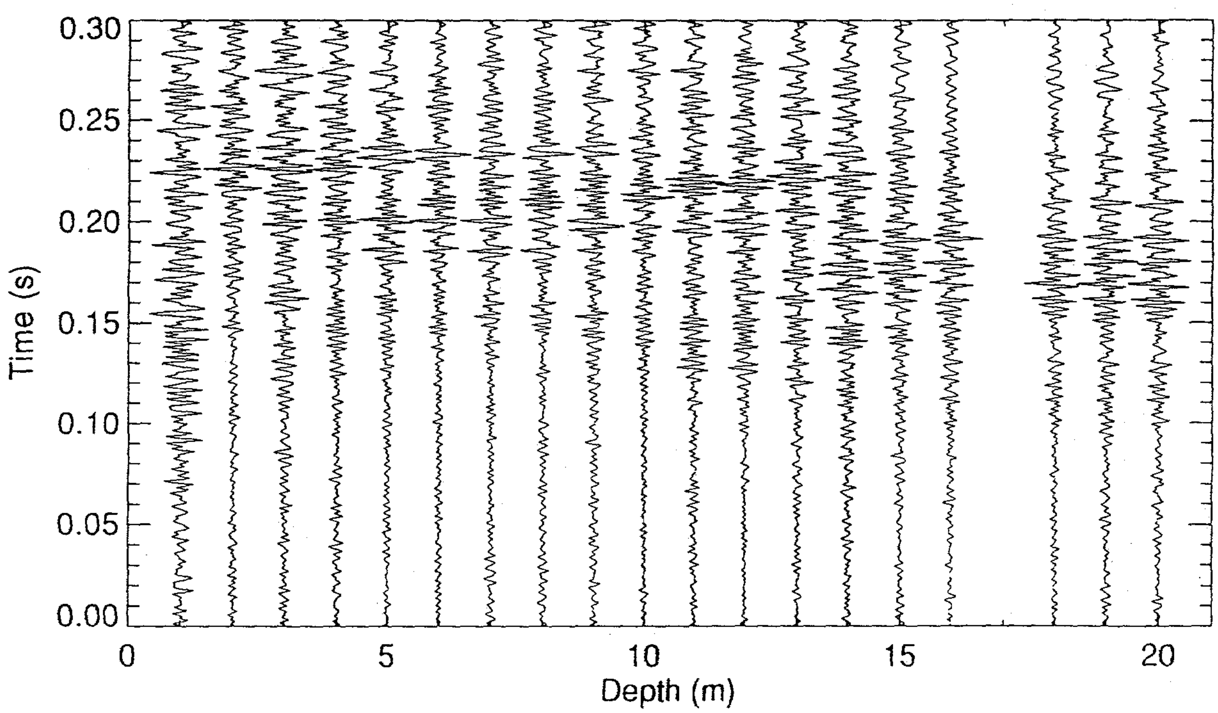

Figure 8: Source gather for data collected with orbital vibrator with source at 15 m depth.

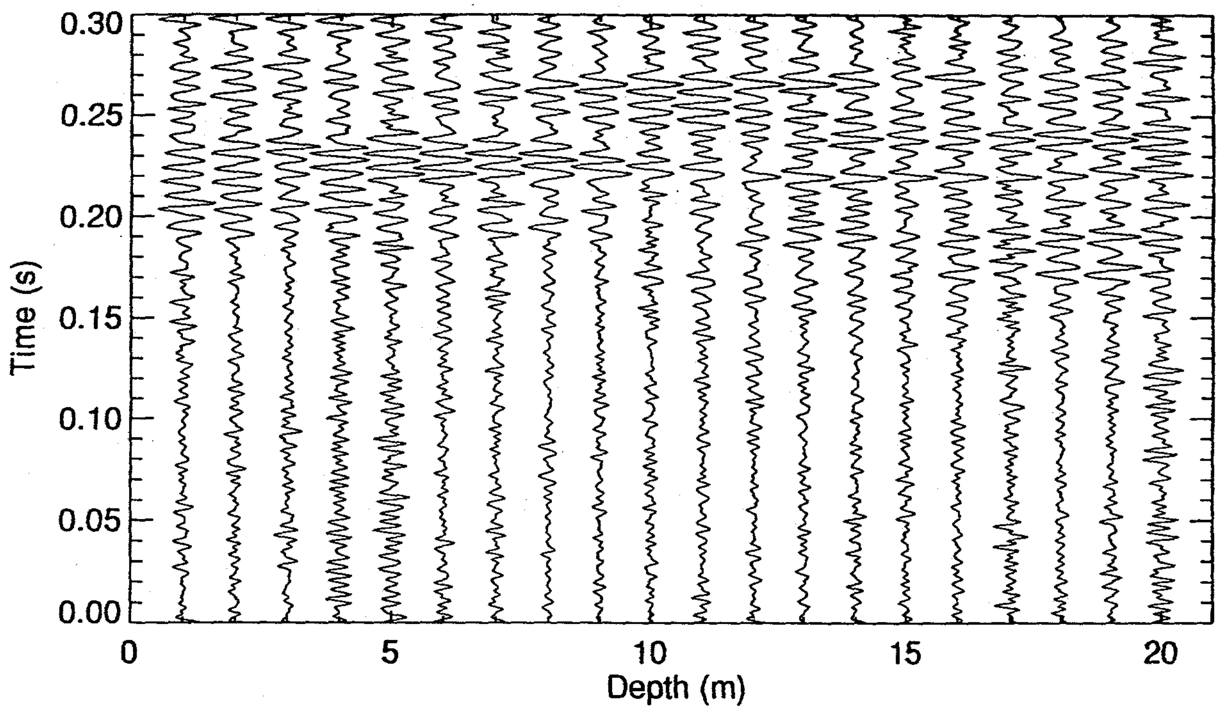

Figure 9: Source gather for data collected with pneumatic vibrator with source at 15 m depth.

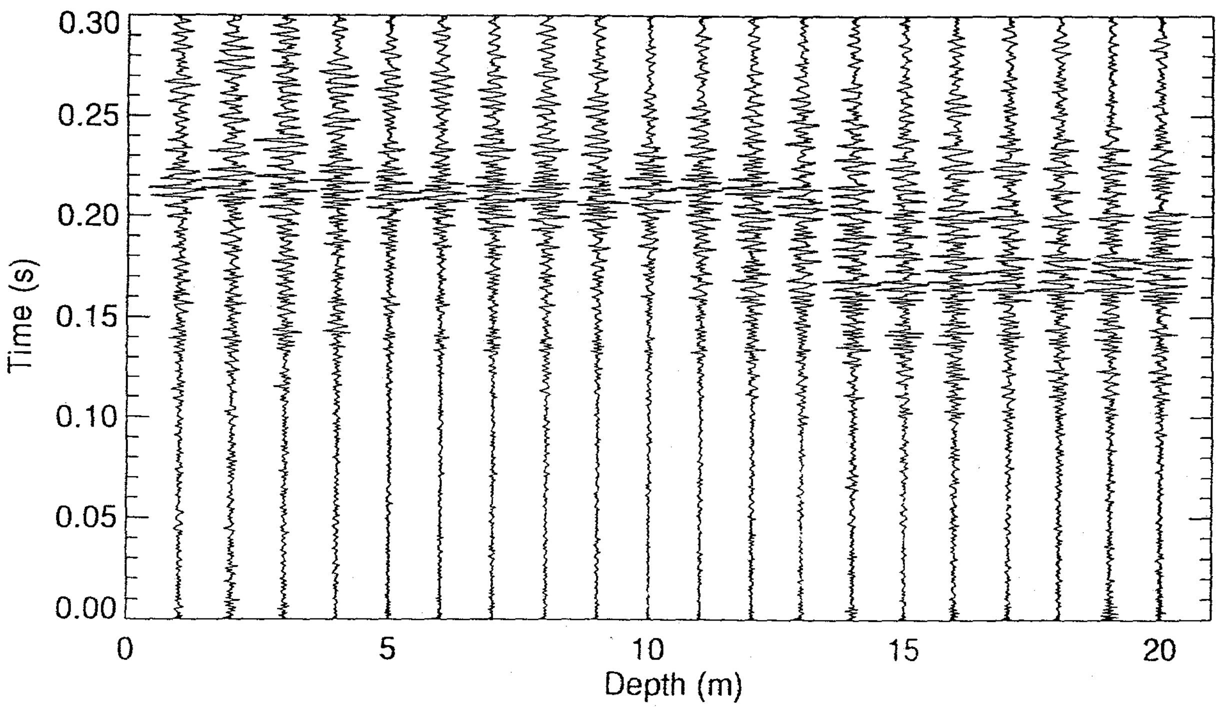

Figure 10: Source gather for data collected with magnetostrictive vibrator with source at 15 m depth.

Source gathers at 15 m source depth for the four sources are shown in Figures 7 to 10. Of these, the airgun and magnetostrictive vibrator show the best P-wave arrival energy across the section at about .10 s, although this arrival becomes more ambiguous for both the sources in the shallower part of the section, but more so for the magnetostrictive source. The P-wave arrival is also present in the deeper parts of the section generated by the orbital vibrator, but is lost in the noise above about 10 m. No evidence of the P-wave arrival is seen on the pneumatic vibrator section.

S-wave arrivals are seen on all four sections at about .15 s below 10 m, but are clearest on the magnetostrictive and orbital vibrator sections. This arrival is also apparent on the airgun and pneumatic vibrator data, but at much lower frequencies. It is uncertain what happens to this arrival above 10 m.

Later arrivals at greater than .19 s are seen on all four section also. There is a general correlation of these arrivals between the magnetostrictive and pneumatic vibrators, although the frequency content and signal-to-noise ratio are significantly less on the pneumatic vibrator section. The airgun and orbital vibrator data show much different later arrivals indicating a significant effect of the source radiation pattern on these arrivals.

CONCLUSIONS

Based on the comparison of frequency spectra and signal characteristics, the magnetostrictive source appears to have the best overall character of the four sources tested, especially for S-wave arrivals. The airgun is dominated by generally lower frequencies, but generates a good P-wave arrival and is easier to field and process, making it an attractive option for quick P-wave surveying. The orbital vibrator also shows good shear wave energy arrivals and, with its ease of operation and generally favorable frequency spectrum, it is still a good source for determining S-wave velocity structure. The pneumatic vibrator performed the worst of the sources and is not recommended if other sources are available.

The restriction of the airgun and orbital vibrator to fluid-filled boreholes can be a potential problem at certain vadose zone sites where water cannot be reliably held in the borehole. This should be taken into account when designing the survey. On the other hand, the clamped sources can prove problematic when weakened casing or PVC or fiberglass casing is involved, and care must be taken to test these clamps in a test casing to ensure that they will not cause any damage to the borehole wall.

It must be kept in mind that the development of downhole sources is an ongoing process and that improvements in source design, clamping mechanisms, operational parameters, and processing may significantly improve the output of any particular source. This has been discussed in terms of the double motor and mass version of the orbital vibrator, the clamp being developed for this same vibrator, and the greater pressure capabilities of the airgun. All these factors must be taken into account, along with the restrictions of the particular site to be surveyed, when choosing the best source to use.

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